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Published in:

Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium

Publication date:

2015

Document Version

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Kjeldsen, P., & Scheutz, C. (2015). Suggested guidelines for gas emission monitoring at danish landfills. In *Proceedings Sardinia 2015, Fifteenth International Waste Management and Landfill Symposium* CISA Publisher.

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SUGGESTED GUIDELINES FOR GAS EMISSION MONITORING AT DANISH LANDFILLS

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SUMMARY: Landfill gas is produced on waste disposal sites receiving organic waste resulting in emission of methane. Regulation requires that the landfill gas is managed in order to reduce emissions, but very few suggestions exist to how the landfill gas management activities are monitored, what requirements to the ability of the landfill gas management to reduce the emission should be set up, and how criteria are developed for when the monitoring activities can be terminated. Monitoring procedures are suggested centred on a robust method for measuring the total methane emission from the site, and quantitative measures to determine the efficiency of the performed emission mitigation is defined. Finally, several principles are presented for how criteria can be developed for when a monitoring program can be terminated.

1. INTRODUCTION

Landfill gas is produced on waste disposal sites receiving organic waste. The release of landfill gas to the environment can give rise to several environmental effects – including the greenhouse effect, created by the content of methane in the gas. The Danish Landfill Directive (Miljøministeriet, 2011) prescribes that the landfill gas is to be managed by either energy utilization, by flaring or by other means, such as mitigation relying on microbial oxidation of the methane in cover soils or constructed biofilters, so-called bio-mitigation technologies. The Directive also states that the gas management is to be properly monitored - very similar to the prescriptions in the European Union Landfill Directive (European Union, 1999). Both the European as well as the Danish directive give only few details in respect to ways of carrying out the monitoring; there is especially very little focus on monitoring of the landfill gas emission and on the efficiency of the implemented gas management scheme. In most cases the efficiency of the implemented mitigation system is not evaluated, since the methane emission from the landfill seldom has been measured.

There is a need to get an overview on the many monitoring approaches and instruments, which are in use, on possible strategies for setting up proper monitoring plans including international experiences in the field. The objectives of this study were to present overviews on possible mitigation technologies for reducing the methane emission from landfills, and on existing emission measurement approaches and instruments, including their advantages, disadvantages and limitations. An additionally objective was to develop best-practice monitoring plans for different mitigation approaches, including stop criteria for termination of the monitoring activities.

The project was carried out for the Danish Environmental Protection Agency and the result came out in a report in Danish (Kjeldsen and Scheutz, 2015). The paper gives a summary of the published report.

2. GAS GENERATION AND EMISSION – A CONCEPTUAL MODEL

The approach takes its outset in the methane balance approach of a landfill, i.e. a description of a conceptual model for gas generation and emission, which shortly describes the most important processes and factors, which govern the gas transport and fate in actual cases. The emission of landfill gas is a result of biological, chemical and physical processes, which takes place in the landfill. The quality and quantity of the emitted gas is depending on several factors, such as waste composition and age, landfill design and maintenance routines at the landfill, as well as local meteorological conditions. By setting up a detailed methane balance it is realized that a thorough understanding of the gas generation and resulting transport, migration, and emission is crucial for setting up efficient mitigation approaches and connected monitoring plans.

The most important parts of the methane balance are shown in Figure 1. Based on this a methane balance equation can be set up:

$$\text{CH}_4, \text{ generated} = \text{CH}_4, \text{ extracted} + \text{CH}_4, \text{ emitted} + \text{CH}_4, \text{ migrated} + \text{CH}_4, \text{ oxidized} + \text{CH}_4, \text{ stored}$$

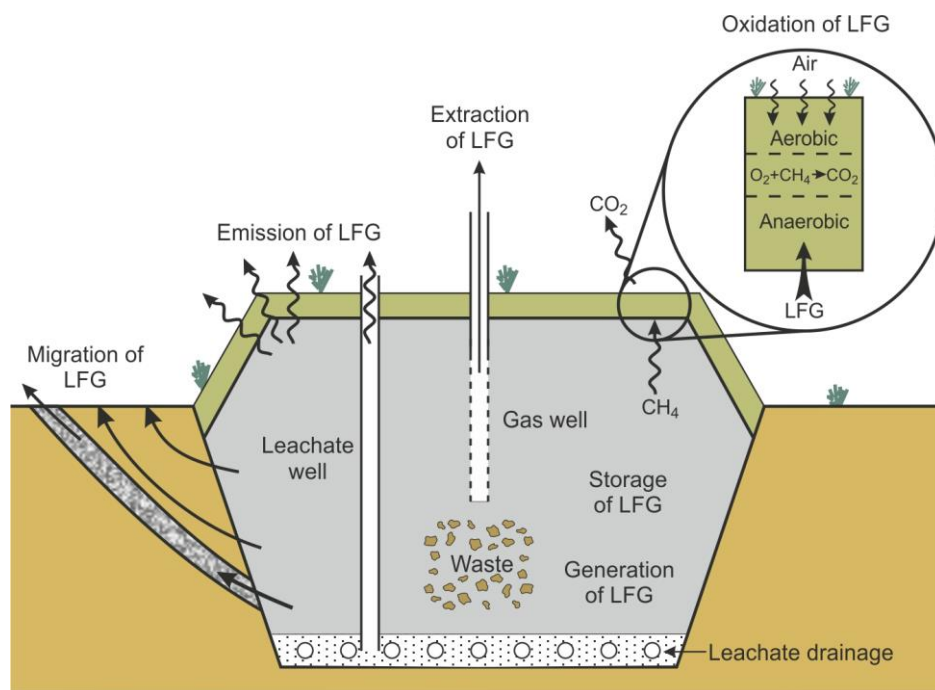


Figure 1. Processes affecting the fate of methane generated in a landfill.

3. EMISSION MEASURING METHODOLOGIES

Through the last 10-15 years several new emission measurement techniques have been tested and demonstrated, and several new dedicated instruments have come on the market. The study reviews several emission measurement techniques, equipment and advantages/disadvantages of the different

approaches. Both more qualitative approaches exist, such as surface emission screening by a FID-detector highly sensitive to low methane concentrations in the ambient air. Also for quantitative measurement of the whole landfill site methane emission several approaches have been developed as reviewed in Kjeldsen and Scheutz (2011). Based on a thorough comparison of the several existing methods, it is concluded that the trace gas dispersion methodology, is the most cost-efficient approach for measuring the whole landfill site methane emission. The method has lately been further developed and validated through a PhD-project carried out at Technical University of Denmark, (Mønster et al., 2014, 2015). Box 1 gives an overview of the use of the trace gas dispersion methods for measuring the whole site methane emission at a landfill. The method is supplemented by initial landfill surface screenings of methane concentrations using a FID-detector or a similar instrument to identify significant emission routes such as areas with imperfect cover or leaking structures such as leachate wells.

4. OVERVIEW ON PREVIOUSLY PUBLISHED LANDFILL EMISSION MONITORING AND CRITERIA

There exist only a few international suggestions to monitoring plans and criteria for termination of the monitoring activity. Reports from Germany, Austria and UK (Stegmann, 2006, Fellner, J. et al., 2008, Environmental Agency, 2010) have been identified and a summary of these are given below.

Germany. Stegmann (2006) is one of the earliest and most concrete proposals for emission monitoring and for how to terminate the monitoring. The report proposes that active mitigation should be carried out, if the gas production exceeds $25 \text{ m}^3 \text{ CH}_4/\text{hour}$ or $5 \text{ m}^3 \text{ CH}_4/(\text{hour and hectare})$ (equivalent in mass units to $16 \text{ kg CH}_4/\text{hour}$ and $3.2 \text{ kg CH}_4/(\text{hour and hectare})$, respectively (the latter again corresponding to $7.7 \text{ g CH}_4/(\text{m}^2\cdot\text{day})$). If the gas produced is less than the above specified values, an assessment should be carried out to evaluate if landfill gas utilization is viable. Alternatively, it is proposed that the mitigation activity is established as methane oxidation in the final soil cover, ensuring that the methane load to the final soil cover is less than $7.7 \text{ g CH}_4/(\text{m}^2\cdot\text{day})$ on average, and that methane concentrations above the soil cover is less than 25 ppm (measured by FID). It is proposed to conduct FID grid measurements; 16 measurements per ha (a grid with a mask length of 25 m), and thus the 80% quantile should not exceed 25 ppm.

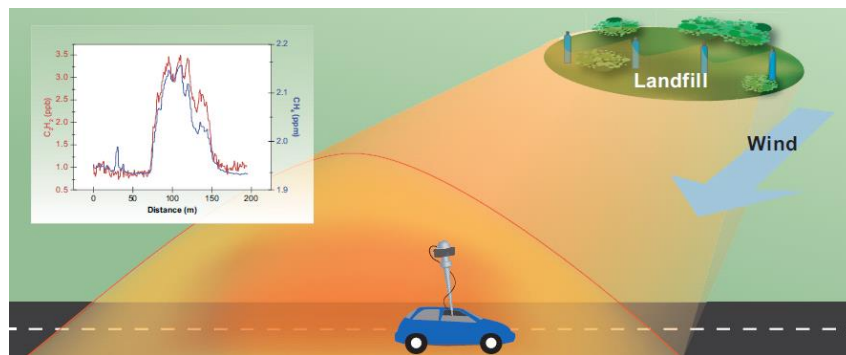
Measurements should be made twice a year (summer and winter). If this criterion never is exceeded over a 10 year monitoring period, the monitoring can be terminated. It should be noted that the above mentioned procedure was developed at a time when methods for measurement of whole site methane emission (such as the trace gas dispersion method) was not available, and that the presence of high emission hot spot areas of very limited size not yet had been recognized (their existence shown by Rachor et al., 2013, Fredenslund et al., 2007). The likelihood that such small size hot spot areas will be identified by a FID measurement in a 25 meters net is very small.

Box 1. The tracer dispersion method for whole landfill site methane emission quantification.

The dynamic tracer dispersion method combines a controlled release of tracer gas from the landfill with methane and tracer concentration measurements downwind of the landfill, using a mobile high-resolution analytical instrument (Börjesson et al., 2009; Scheutz et al., 2011). The method has been used successfully since about the late 1990s, and with new developments in analytical technology it has become a powerful tool for quantifying methane emissions from landfills (Mønster et al., 2014; 2015). The tracer dispersion method in general is based on the assumption that a tracer gas released at an emission source, in this case a landfill, will disperse in the atmosphere in the same way as methane emitted from the landfill will disperse. Assuming a defined wind direction, well mixed air above the landfill (causing the emitted methane and released tracer gas to be fully mixed), and a constant tracer gas release, the methane emission rate can be calculated as a function of the ratio of the integrated cross-plume concentration of the emitted methane and the integrated cross-plume concentration of the released tracer gas, as follows:

$$E_{gas} = Q_{tracer} \cdot \frac{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{gas} dx}{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{tracer} dx} \cdot \frac{MW_{gas}}{MW_{tracer}}$$

Where E_{gas} is the methane emission rate ($kg\ h^{-1}$), Q_{tracer} is the release rate of the tracer gas ($kg\ h^{-1}$), C_{gas} and C_{tracer} denote cross-plume concentrations (ppb) above the background concentration, MW denotes molecular weights and x corresponds to distance across the plume. The tracer dispersion method has been successfully applied at more than 25 Danish landfills (Mønster et al., 2015). Guidelines for measurement performance have been established including: 1. On-site mobile screenings for proper tracer release configurations, 2. Off-site screening for identification of local methane sources and finally 3. Plume traversing and 4. Data processing.



A methane production corresponding to a load of $7.7\ g\ CH_4/(m^2 \cdot day)$ may be oxidized in the final soil cover - assuming that the cover most of the time has a good ability to transport the gas through the cover (as controlled by the soil's permeability and diffusivity) and that the load is evenly distributed and not concentrated in the high-loaded hot-spot areas. Clayey soils will rarely have sufficient gas permeability and diffusivities - especially in autumn and winter where the water content can be so large that gas transportation is not possible. In such cases, high gas pressures can build up within the waste volume with a high risk of forming hot spot emission areas, resulting in a low methane oxidation efficiency.

Austria. Proposed procedures from Austria are close to above-described "Stegmann procedure" (Fellner et al., 2008). However, additional requirements are set up for emissions from the soil

surface, which should be below $0.5 \text{ m}^3 \text{ CH}_4/(\text{hour and hectare})$ (corresponding to $0.77 \text{ g CH}_4/(\text{m}^2\cdot\text{day})$ or 10% of "Stegmann value". An efficiency of methane oxidation in soil covered of at least 90% is thus anticipated. For a 4-hectare landfill, the emission corresponds to $1.3 \text{ kg CH}_4/\text{hour}$.

England. England is probably the country with the longest record in setting up requirements to monitoring methane emitted from landfills. The British Environmental Agency has set specific requirements for methane emissions from landfills (Environmental Agency, 2010). The requirements apply to both operating and closed landfills. For landfills in operation there exist requirements for both final covered and temporarily covered stages. A temporary covered stage is defined as a stage, which has not received waste for a period of 3 months or longer. In addition to making specific emission value requirements, specific requirements to the monitoring method, strategy, conditions and frequency of measurement are set up.

The monitoring of methane emissions are divided into two phases. The first phase examines whether there are significant methane emissions from installations (eg. gas and leachate collection wells) and from specific hotspots in the cover soil layer (eg. cracks in the cover soil layer). A systematic methane semi-quantitative screening of the surface with a handheld FID is performed.

Areas or installations with elevated methane concentrations are measured are remediated before a follow up with Phase 2 monitoring. This phase involves quantitative methane emission measurements. The following requirements are set up for Phase 1 before it is possible to follow up with Phase 2 monitoring:

- The methane concentration in the air above the cover sheet: $<100 \text{ ppmv}$ in the majority of the final covered area
- The methane concentration in the air close to the installations: $<1,000 \text{ ppmv}$

In the second phase methane emissions from the cover soil layer (or the temporary cover layer) is measured by means of stationary flux chambers, where a large number of measurements are performed in a selection of representative locations. Initially, the stages are divided into zones. A zone is defined as an area in which the cover is uniform and homogeneous. An average emission is calculated based of the performed flux measurements for each zone. Temporary covered stages must also be monitored if they have been or are expected to be present at the site for a period of 12 months or longer. The temporary covered stages are also divided into zones. The following requirements apply for average methane emissions:

- Finally covered zones: $0.001 \text{ mg CH}_4/ \text{m}^2\cdot\text{second})$ corresponding to $0.09 \text{ g CH}_4/(\text{m}^2\cdot\text{day})$
- Temporary uncovered zones: $0.1 \text{ mg CH}_4/ \text{m}^2\cdot\text{second})$ corresponding to $8.6 \text{ g CH}_4/(\text{m}^2\cdot\text{day})$

The first monitoring (both including Phase 1 and Phase 2) is to be performed within one year after the final cover is in place. If emissions exceed the prescribed emission requirements, measures have to be initiated to reduce the emissions. After this a new round of measurement of emissions is to be carried out. If the average emission is within the acceptance criteria, follow-up monitoring can be performed as methane screening using a FID. If this is within the acceptance criteria for screening, the methane emissions found at the former round of emission measurements is to be reported. There should be annual-reporting of methane emissions to the authorities. Criteria for termination of the monitoring program is not mentioned.

5. SUGGESTED EMISSION MONITORING APPROACHES

Emission monitoring is to be carried out not only in the active period where waste is received at the site, but also in the after-care period where waste is no longer received. The monitoring is to be continued until significant emission will no longer occur even after that the implemented mitigation measures are terminated. What a significant emission is, or in other words what an appropriate stop criteria for monitoring activities is (for instance in tons CH₄/year), is highly debated, and no consensus has been reached. The question will be further dealt within the next section.

Based on information gathered from the Danish landfills the following scenarios in respect to mitigation approaches can be set up:

1. LFG is collected and utilized in a gas engine or other energy utilization facility
2. LFG is collected and flared
3. LFG is collected and actively (by the use of pumps) led to a methane oxidizing biofilter
4. LFG is led passively (without the use of pumps) to a methane oxidizing biofilter
5. LFG is led passively (without the use of pumps) through the landfill top soil cover or biowindows
6. No established mitigation facilities. LFG quantity and fate unknown.

Besides, several scenarios on different landfill cells within one landfill facility might exist. There might also be cases where one scenario follows another (for instance establishing a biofilter (scenario 3) when a utilization facility (scenario 1) has become old and no longer is cost-effective.

The trace gas dispersion methodology is suggested as the core methodology in monitoring plans for methane emissions from landfills in combination with initial emission screening efforts – for all mentioned scenarios. The suggested monitoring plans for the different scenarios are summarized in Box 2. The box also presents ways of estimating mitigation efficiencies based on the methane balance approach for the landfill.

Additional monitoring plans and measures are suggested in case that the required mitigation efficiency is not met (we suggest that the estimated mitigation efficiency should not be under 80% - as shown in Box 2). This could be done by additional surface methane screening to identify significant release points or areas. Any identified major leaks should be repaired.

Box 2. Overview on monitoring principles for the six defined scenarios.

Monitoring – when LFG is collected (Scenarios 1-3)

- Gas collection is calculated based on recorded gas flow (m³/hour) and methane content (%vol. recalculated to kg/m³)
- Emission of methane from the landfill is measured using the trace gas dispersion method (or similar method) – initially twice a year
- The collection efficiency, E (%) is calculated:

$$E = 100\% \cdot \text{CH}_4, \text{ collected} / (\text{CH}_4, \text{ collected} + \text{CH}_4, \text{ emitted} + \text{CH}_4, \text{ oxidized})$$
- CH₄, oxidized is either to be measured, set to the IPCC recommended default value of 10% of emitted methane, or to be neglected. The degree of methane oxidation can be established by measuring the stable carbon isotopes in the raw landfill gas and in the emitted gas. This method is at the moment still in development. If it is known from initial studies that the methane do not undergo significant oxidation due to release from hot spots, leachate wells, etc., it is recommended to neglect the oxidation.
- If the calculated collection efficiency (E) is lower than 80%, supplementary monitoring and measured to optimize the mitigation system is initiated

Monitoring – at passive gas supply via collection/distribution system to biofilter(s) (Scenario 4)

- The supply of landfill gas is shortly circuited with free release of gas to the atmosphere
- Emission of CH₄ is measured using the trace gas dispersion method (or similar method) both during normal operation and during free landfill gas release
- Mitigation efficiency, E (%) is calculated:

$$E = 100\% \cdot (1 - \text{CH}_4, \text{ emitted during normal operation} / \text{CH}_4, \text{ emitted during short circuiting})$$
- If the calculated collection efficiency (E) is lower than 80%, supplementary monitoring and measured to optimize the mitigation system is initiated

Monitoring – at passive supply to landfill soil cover/constructed biowindows (Scenario 5-6)

- It is assumed that the gas supply cannot be circuited
- Emission of methane is measured using the trace gas dispersion method (or similar method) both during normal operation
- It is preferred that the methane emission is measured prior to the establishment of the passive mitigation system, ELSE
- Methane generation is estimated by use of a landfill gas generation model (the Danish PRTR approach is recommended, Scheutz et al., 2009)
- An estimate on the mitigation efficiency, E(%) is calculated:

$$E = 100\% \cdot (1 - \text{CH}_4, \text{ emitted during normal operation} / \text{CH}_4, \text{ generated (estimated via model)})$$

or

$$E = 100\% \cdot (1 - \text{CH}_4, \text{ emitted during normal operation} / \text{CH}_4, \text{ emitted before established mitigation system})$$
- If the calculated collection efficiency (E) is lower than 80%, supplementary monitoring and measured to optimize the mitigation system is initiated

6. CRITERIA FOR TERMINATION OF EMISSION MONITORING

As already described a monitoring plan should contain a description on when it is safe to terminate the monitoring activities. The description should be quantitative and concrete in form of a stop criterion for the emission (depicted in kg CH₄/hour or tons kg CH₄/year). It is well-known that the landfill gas generation can continue for centuries, but also that the generation rate steadily decreases with time. During the decrease the “natural” oxidation of methane (the oxidation intentionally or unintentionally taking place in the landfill soil cover) would be more significant (due to longer gas retention times in the cover), which may decrease the emitted methane even further. On the other

hand it is unrealistic to expect a state of zero emission, since there always will be sub-optimal locations from which emission may occur.

During the work we identified four different principles for establishing a stop criterion for methane monitoring:

1. Gas generation can passively be mitigated by “natural” methane oxidation in the final soil cover,
2. The measured whole site methane emission is lower than the detection limit of the trace gas dispersion methodology,
3. The whole site methane emission (per unit surface area) is lower than similar surface area normalized emissions from natural ecosystems (wetlands)
4. Costs for continued mitigation will be much higher than mitigation costs in other societal sectors (measured in €/tons CO₂-equivalence).

6.1 Passive methane oxidation in final soil cover

At a certain time, it can be expected that the gas generation is so low that a passive handling based on methane oxidation in the final soil cover can reduce the methane emission to an acceptable low level - even taking into account a certain spatial variability in the gas loading to the final soil cover. In case that the existing activities for mitigating the methane emission is based on an active extraction of gas, the gas engine (or alike) can be by-passed for a short period where total methane emissions is measured (as described in the previous section). Based on the total measurement, an aerial distributed gas load can be evaluated (assuming that the total area of the final soil cover is known and assuming an evenly distributed load to the cover). If the average load of methane is less than 10 g/(m²·day), it is expected that the final soil cover can oxidize 90% of the methane loading.

This means that the release of methane from the landfill will be a maximum of 1 g/(m²·day) or less. A high methane oxidation in the cover layer assumes that the soil, which is used for the cover layer has sufficiently high gas permeability for the gas to be transported through the soil cover. Soil covers on Danish landfills often contains clayey soils (in order to reduce infiltration of excess precipitation). Clayey soils will over large periods of the year exhibit high water content leading to very low gas permeability as well as low gas diffusivity, resulting in high resistance towards gas transport. Instead, the gas will find its way to areas with higher gas permeability, emits through installations such as leachate wells, or - if possible - migrate to the surrounding areas containing soils of higher gas permeability. Before active mitigation activities are shot down, it is important to ensure that the gas can be transported through the final soil cover. To test whether the covering layer can actually reduce the present methane after closure of mitigation activities, monitoring should be carried out before and after shutdown (at least a new total measurement of methane emission after closure). Total measurement may in this case reveal that methane emissions are unacceptably high. As a consequence, this may imply that existing mitigation activities must be continued yet some time, or alternatively that biowindows are established in areas with a low-permeable soil cover.

6.2 Total methane emission lower than detectable

As already stated we recommend that measurement of the total emission from the landfill make out the core monitoring activity, and recommend that the tracegas dispersion methodology is used. Detailed investigations using the methodology have shown that the detection limit for methane emission measured with a state-of-the-art version of the methodology is about 1 kg CH₄/hour. If the total methane emission is lower than this value, it becomes difficult to prove that the landfill emits methane into the environment. A stop criterion could be that the emission must be less than 1 kg CH₄/hour for the landfill - achieved after shut down of all active mitigation actions at the site. For a landfill with an area of 4 ha this corresponds to a methane emission of 0.6 g CH₄/(m²·day).

6.3 Total methane emission equivalent to emissions from natural eco systems

Landfills are globally one of the most important anthropogenic sources of methane emission (Bogner et al., 2008). Besides anthropogenic sources, there are several natural methane sources, such as lakes, rivers, wetlands, etc. Methane emissions from natural sources are generally unregulated and could therefore be a reference for emissions from anthropogenic sources. It might be argued that there should not be set up strigther emission limits to anthropogenic sources (eg. normalized per unit area) than typical emissions from natural sources. A recently published scientific article (Ortiz-Llorente & Alvarez-Cobelas, 2012) reviewed the literature on methane emissions from natural sources. They found an average annual methane emission from wetlands (defined in the article as "sites where water is at or near the soil surface for a significant part of the growing season") of 470 g CH₄/(m²·year) - equivalent to 1.3 g CH₄/(m²·day) - based on 126 references. It should be noted that the value is of the same order as the above detection limit for total emission measurement.

6.4 Optimization of sociatal expenses for mitigation of greenhouse gas emissions

Setting up a relatively low stop criterion for methane emission will generally result in limited contribution to the greenhouse effect from Danish landfills. However, it will also mean that mitigation activities must be maintained for many years in the after-care period resulting in an overall low reduction during the period (measured in tons of reduced emissions of CO₂-equivalents). By documenting the cost of operating the mitigation activities (including costs for maintenance and monitoring of the mitigation activities) the resulting mitigation costs (in €/tonnes CO₂-equivalents reduced) is calculated and compared with similar normalized prices for other mitigation activities carried out in Denmark. Here one can argue that there should be proportionality between the various initiatives. If the normalized cost for mitigation of methane emissions from a landfill is considerable higher than normalized costs for other of the society's optional mitigation activities, it could be argued that the landfill methane emissinon mitigation no longer should be carried out.

6.5 Overview on stop criterion

The first three principles described above gave stop criteria in the order of 1-3 kg CH₄/hour for a small landfill (area of 4 ha) as shown in Table 1. The last mentioned criteria can only be evaluated by additional economical evaluations, and a political decision on how high mitigation costs the society wants to pay.

Table 1. Overview on stop criteria for methane emission based on different theoretical principles. Also accept criteria for monitoring plans reported in literature from different countries are shown.

<i>Principle</i>		<i>Levels for methane supply to cover soil layer</i>		<i>Stop criteria for methane emission</i>	
		<i>g/(m²·d)</i>	<i>kg/h</i>	<i>g/(m²·d)</i>	<i>kg/h</i>
Theoretical established stop criteria	1. Passive methane oxidation in soil cover	10.0	16.5 ^a	1.0 ^e	1.6 ^e
	2. Total methane emission lower than detectable	n.d.		0.6 ^a	1.0
	3. Methane emission similar to emissions from natural eco systems	n.d.		1.3 g	2.2 ^a
	4. Optimization of expenses to mitigate societies greenhouse gas emissions	c.s.		c.s.	
				<i>Accept criteria for methane emission</i>	
				<i>g/(m²·d)</i>	<i>kg/h</i>
International suggestions	Germany (Stegmann, 2006)	7.7	12.7 ^{a,b}		
	Austria (Fellner & Prantl, 2008)	n.d.		0.77	1.3 ^a
	England			0.09 8.6 ^{d,c}	0.15 ^a 14.3 ^{a,c,d}

n.d.: not defined c.s.: case specific
a): for a 4 ha sized landfill
b): simultaneously all measured surface FID-readings < 25ppmv
c): valid for temporary covered cells
d): simultaneously all measured surface FID-readings < 100 ppmv and FID-readings at installations such as gas or leachate collection wells < 1000 ppmv close to the installation.
e): assumes that the soil cover has an oxidation efficiency of 90% in average, and besides that the soil cover has the necessary gas permeability/diffusivity

7. CONCLUSIONS

Both the European Union Landfill Directive and the related Danish Landfill Directive demands that gas generated at a landfill is properly managed and that monitoring plans are set up. However, none of the directives gives any details on how monitoring plans should be set up, nor any recommendation to for how long monitoring should be carried out in the after-care period of the landfill. Based on a review on existing suggested monitoring approaches from European countries and evaluation of existing methods for measuring total emissions from landfills, a monitoring approach is suggested to the Danish Environmental Protection Agency.

The approach takes its outset in the validated tracer gas dispersion method as a core element in the approach and calculates under different mitigation approaches quantitative mitigation efficiencies. Requirements to the mitigation efficiency are set up with a description on measures to be taken if the mitigation activities do not live up to the requirements. Finally, emission criterias for terminating a monitoring procedure is discussed and four different approaches are presented. A final approach for termination is not given.

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